

Modelling of Industrial Hybrid Bonding Processes considering Fluid-Structure-Interaction

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Abstract. *The subject of the work presented is focused on self-pierce-riveting and clinching in combination with adhesive bonding. In the industrial process chain the rivets and clinch-points are set before the adhesive is cured. A FEA reference model is developed for the elementary mechanical joining processes. The model is then expanded to consider the displacement of the liquid adhesive, including associated internal pressures. Coupled fluid-structure simulations, which include the interaction of the solid matter influenced in the mechanical joining process and the fluid adhesive, are presented. In a last step a surrogate model for the multi-point hybrid joint is developed and applied to industry-relevant structures.*

1 INTRODUCTION

Adhesive joint manufacturing usually starts with the application of the liquid adhesive on one of the adherents to join; thereafter, the second adherent is placed such to achieve an adhesive bonded gap between the parts to be bonded. The last step consists on curing the adhesive until final strength is achieved, a process which in some industrial applications is being accelerated by appropriate means, as heating. In recent years, in the automotive industry, bonding is increasingly being used to achieve lightweight structures with high crash performance. Adhesively bonded joints ensure a much smoother load transfer, higher joint capacities, and stiffer connection. In the automotive industry typical connections are, amongst others, bonding complements connections in the car main body (and doors, hoods) that are achieved with traditional mechanical fastening, as for example clinching, hammering and riveting; their main advantage lie in short process times, although with lower total bonding strengths. Specific advantages of adhesively bonded joints and mechanical fastening can be combined in form of hybrid joints, which yield in synergies of manufacturing, strength, crash behavior, and durability performance.

In a specific hybrid bonding process increasingly used in industry, the so called “fixation method”, liquid adhesive is applied between two metal sheets, then mechanical joining is performed while the adhesive is yet uncured, after which the adhesive is cured. Depending on the type of mechanical fastener, e.g. considering hammering or rivets, the hybrid joint can take different designations. The hybrid adhesive-hammering and the hybrid adhesive-clinching process include large plastic deformation of the metal sheets, in presence of the pasty liquid adhesives. The hybrid adhesive-riveting process additionally includes the fracture of the upper metal sheet, influenced by the presence of a pasty fluid. Critical issues in such hybrid joining processes are the formation of adhesive pockets in the region of the mechanical junctions, the potential presence of air bubbles in the adhesive, and the usually large global deformations of the metal sheets between the mechanical joints.

Numerical modelling of aforementioned hybrid joining processes makes it necessary to consider various physics: all effects related to the uncured—thus liquid—adhesive are associated to fluid dynamics, while solid mechanics is needed for the mechanical fasteners, and metal sheets. Since both effects act simultaneously, taking into account the Fluid-Structure-Interaction (FSI) is fundamental. In hybrid bonding processes hydrostatic pressures inside the adhesive pockets can reach very high values, such to lead to plastic deformations of the metal sheets. When transferring high pressures, the exchange process of boundary conditions between the software for the solid metal forming process and the code for simulation of the fluid flow of the liquid adhesive is limited by the stability of the FSI simulation. This requires a careful selection of an adequate code coupling module. On the basis of experimental studies the authors present simulations for the numerical descriptions of hybrid joining processes. Different examples of simulations of hybrid adhesive-clinching, and adhesive-riveting, processes will be presented; from simple—academic—geometries to industry-relevant structures. The elaborated FSI simulations are able to shed additional light on the insights, and on the influence of several key parameters on the process.

2 COUPLING STRATEGY

In hybrid joining processes strong interactions between the two elementary joining steps occur, so that process parameters that have been determined as optimum separately cannot be transferred to the hybrid technology directly. Beside experimental studies, numerical descriptions of hybrid joining processes [1,2,3] are able to shed additional light on the insights on the influence of several key parameters. Because of the strong interactions between the metals and the adhesives, simulation of hybrid joining processes must integrate liquid adhesives flow and mechanical joining processes in parallel.

Literature reports on several experimental studies on hybrid joining applying the fixing method. Correlations between the quality of the mechanical joint, the adhesive and the global deformation were partially investigated using experiments [4,5,6,7]. The main techniques to measure the quality of hybrid bonded specimens are metallographic sectioning of cured compounds and tactile or inductive measuring of deformation while curing. Also the numerical analysis of final cured hybrid joints under mechanical loads is state-of-the-art, see [8,9,10]. The simulation of hybrid bonding processes facing the flow of liquid adhesive including the comparison with experimental data is the topic of one of the authors in [11,12,13].

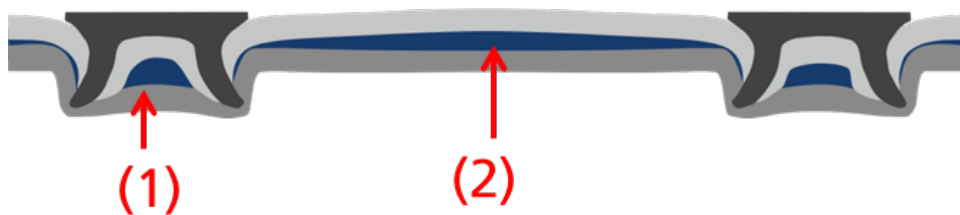


Figure 1: Formation of adhesive bags (1) in hybrid junctions and (2) between hybrid junctions

Stepping in the detail of the simulations, both the elasto-plastic flow processes of the metal parts and the viscous flow of the adhesive must be calculated simultaneously using a fluid-structure-interaction (FSI) simulation. In this case also the strong interactions between the liquid and the solid material must be numerically coupled.

One coupling strategy is to connect a structural with a fluid mechanical code using a special coupling software tool. The transferring software will couple for example a structural domain calculated using structural FEM with a fluid domain calculated using CFD by the exchange of boundary conditions at corresponding time steps. This kind of coupling is implemented in some general purpose simulation packages like Ansys® or Abaqus®. Alternatively a third party software product like MPCCI can be used. But the linking of one software product for the solid metal forming process and another software for simulation of the fluid flow of the liquid adhesive is limited when strong coupling is involved.

Another method is to use advanced material models to handle the liquid flow in a structural numerical code only. Using the Arbitrary Lagrangian Eulerian (ALE), the Coupled Euler Lagrangian method in Abaqus[®] (CEL), and the fluid-structure coupling analysis using Abaqus[®] in combination with MPCCT[®] and Ansys[®] Fluent[®] is tested. All methods required high computational effort, even for a single point hybrid joint. The use of surrogate models is able to significantly decrease the complexity of the numerical problem and to describe industrial structures with multiple hybrid joints using a structural numerical code only.

3 SINGLE POINT CLINCH-BONDING AND RIV-BONDING PROCESSES

The basis of the simulation of hybrid bonding processes are stand-alone simulations of mechanical joining processes of clinching and self-pierce-riveting. The models include the experimentally determined strength and yield curve of metal on one hand, and the rheological flow behavior of adhesive. At first a reference model for the elementary clinching and the self-pierce-riveting is qualified for the simulation. In self-pierce-riveting the rivet fractures the metal sheet, which has to be taken into account. Due to the low sensitivity of the failure model on the geometry and force curves a simple ductile model is used. Comparisons between experimental and numerical results (Fig. 1 for the clinch-bonding) indicate that the approach for single point clinch-bonding and riv-bonding processes is validated.

Aforementioned simulations allow understanding the formation of adhesive bags in the mechanical joining zone. Fig. 1 shows the simulation results for hybrid adhesive-clinching of steel-aluminum and steel-steel pairing of sheets after 0.2sec, 0.5sec and 1.0sec. In each time frame the results of the steel/aluminum pairing are shown on the left side and the steel/steel pairing is shown on the right side. The steel sheets are located on the top of the joints and the aluminum sheet on the bottom. The coloring visualizes the von Mises stresses of the metal sheets. The adhesive layer is colored in gray.

The aluminum sheet has a lower stiffness so that it is more deformed under the acting forces. As a result the total amount of the enclosed adhesive at time 0.5sec is higher for the steel/aluminum combination. The punch causes a displacement of the adhesive from the center in radial direction in all material combinations, leading to an accumulation of adhesive in the area of the outer diameter of the punch. At the end of the process the two distinct pockets of glue in the joint zone are bigger for the pairing aluminum/steel. Similar results were obtained for riv-bonding process, which allowed concluding that the simulation method developed here is able to describe the physical processes of single point hybrid bonding correctly.

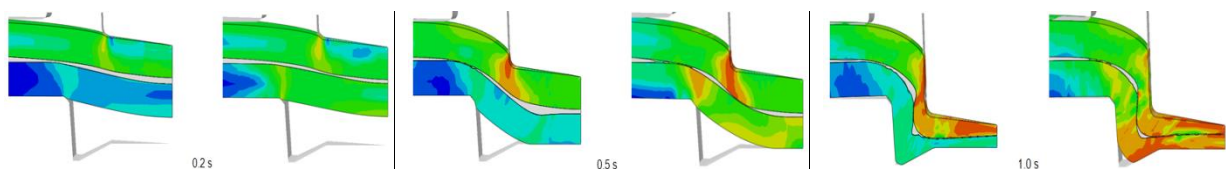


Figure 2: Simulation of the clinch-bonding (after 0.2 sec, 0.5 sec, and 1.0 sec, respectively)

4 MULTI POINT RIV-BONDING PROCESSES

Industrial applications almost always involve multiple joints embedded in 3D geometries, mostly without symmetries to be exploited. To step forward to this applications the methods of simulation need further improvements. For this purpose the individual hybrid joining points of a complex part are modeled using simplified surrogate models. This surrogate model describes the time dependent rate of adhesive flow and the displacement of the metal sheet as boundaries using a geometric cut at a given radius around the respective joining point. The simulation is divided in a local 2½D model and global 3D model with a cylindrical connection region circumvented around the jointing point (see Fig. 3). Here the local model describes the single hybrid joint using FSI and axial symmetric modeling and the global model describes the flow of adhesive through a 3D structure using imported time dependent boundary conditions derived from the local model.

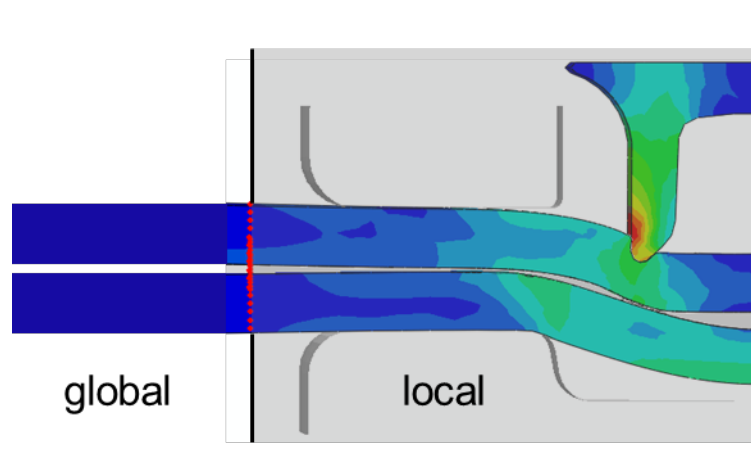


Figure 3: Coupling of local 2½D model and global 3D model with a cylindrical connection region for the riv-bonding process

Using a first python-script, the time dependent results of deformation and adhesive flow occurring in the connection region from the local 2½D FSI simulation are derived and stored in a file. It is possible to set up a database of typically applied hybrid joints by collecting the result files of their local simulation for subsequent use. If required, the extracted flow and deformation data for a special joint type can be transformed into FEM-boundaries acting on each connection region of the global 3D multi-point model. The transformation of data-files to boundaries is automated by a second python-script, which derives the changes in dimension, rotation, translation, time-shift and meshing from the local to the global model. Using the two python-scripts allows to automatically build-up of complex multi-point hybrid joint geometries based upon libraries of materials and adhesive properties, as well as typical hybrid joint elements.

The simulation using a surrogate model enables the modelling of much more complex, industry-related, structures without exceeding the capacity of commercially available computer architectures. The validation of the surrogate model at geometrically simple

samples is the basis to describe more complex structures coming close to components of automotive body-shells.

This is illustrated by the following example of a cap profile with three hybrid junction points in the flange: the adhesive layer in the flange is pressed to its final shape driven by the hydrostatic stresses resulting from the hybrid joining process. The flow of adhesive caused by the mechanical joining process leads to a final deformation of the metal flange of the cap profile. This final deformation is shown for different cut views in Fig. 4.

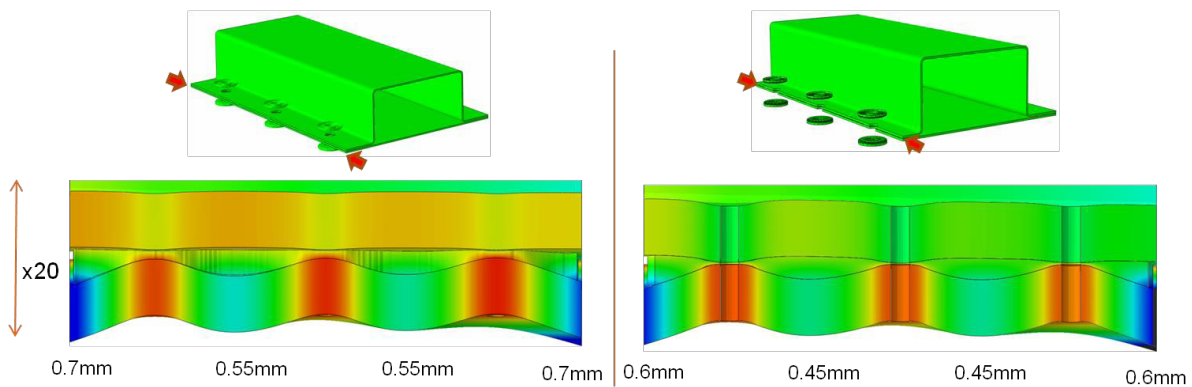


Figure 4: Deformation at the flange of the cup profile at two different cut positions. Colors symbolize the amount of deformation in vertical direction $[-0.5\text{mm to }+0.05\text{mm}]$. The vertical axis is scaled with a factor of 20. Numbers denote the height of the final adhesive gaps between the two metal sheets.

5 CONCLUSIONS

The numerical description of the mechanical joining and the adhesive flow helps to understand the hybrid processes and to create solutions for critical joining tasks in industry. Based on the increased process knowledge made possible by the numerical simulations, options for process-optimization of clinch-bonding and riv-bonding processes are derived, leading to a better undercut in the mechanical joint and reduced pockets of adhesive. Process modifications can be used in order to achieve smaller adhesive bags and bigger undercuts in single point joints.

However, the developed simulations for the single point joints are associated with high computational times. Using the developed surrogate model it is possible to study in detail the time-dependent process of adhesive bag formation in multi-point joining processes. The investigations showed that adhesive bags results as a merging of ebbing waves of adhesive. The worked out techniques can be expanded for industrial use to serve as a tool for further optimization of processes. The simulations provide a basis for further numerical investigations of different hybrid joining processes.

6 ACKNOWLEDGEMENT

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